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Procedia Engineering 67 (2013) 78 – 84

**Procedia
Engineering**www.elsevier.com/locate/procedia

7th Asian-Pacific Conference on Aerospace Technology and Science, 7th APCATS 2013

High Altitude Cycloidal Wind Turbine System Design

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Abstract

As a novel high altitude wind power system, this paper describes a cycloidal wind turbine mounted on a tethered balloon or parafoil. The rotor system was designed conceptually and the performance was estimated. The rotor blade span length is 10 meters and its diameter is 10 meters. When the rotor operates at 1,500 meters above ground, it produces 4.6 times more energy by the balloon tethered model. The parafoil tethered rotor power generation becomes 4.1 times at the same condition, which is a little smaller comparing with the balloon tethered model. The reason is its energy consumption at low wind speed condition to produce supplementary lifting force through mode conversion.

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Selection and peer-review under responsibility of the National Chiao Tung University

Keywords: High altitude wind turbine, Cycloidal wind turbine, Balloon, Parafoil, Tethered cable

1. Introduction

Wind power is the most useful renewable energy. Between 2005 and 2010 the average annual growth rate in new installations was 27.6 percent [1]. The most important factor in wind energy generation is selection of good location where wind flow is strong and consistent. In this reason, many wind turbines are constructed on mountains or offshore sites using tall towers. The tower height has grown from 40 meters to 90 meters over the past 20 years. This trend is still going on to exceed 100 meters. However, even 100 meters or 150 meters, it is not sufficient increment. Typically, in daytime, doubling the altitude increases the expected wind speed by 10%, which means the expected power by 34% more [2]. Therefore, recent years have seen significant advances in technologies to generate electricity from high altitude winds that of hundreds or thousands meters above. Some of these technologies are KiteGen using controlled tethered airfoils [3], Magenn aerostat using a vertical-axis wind turbine [4], a parawing on ships [5], and several non-airborne concepts [6]. As another novel high altitude wind

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power system, this paper describes a cycloidal wind turbine mounted on a tethered balloon or parafoil as shown in Fig. 1 [7].

2. Cycloidal Rotor

Cycloidal rotor consists of several blades which are parallel to the axis and rotating with periodic pitch angle variation as shown in Fig. 2. This mechanism has been applied to aircraft and marine propulsion systems in addition to energy generation turbines [8]. Figure 3 shows some applications of cycloidal rotor developed in Seoul National University. The VTOL aircraft cyclocopter showed good hovering and forward flight capability [9]. Wind turbines and hydraulic turbines resulted in good numerical and experimental performance [10]. As a wind turbine, cycloidal rotor shows high efficiency by active blade pitch angle control according to wind speed and direction change. Optimization of cycloidal rotor design variables such as pitch and phase angle variations, number of blades, airfoil, tip speed ratio, solidity, and other structural parameters is important; however, in this feasibility study phase, almost all rotor design variables were determined without detail parametric studies with reference to the previous researches.

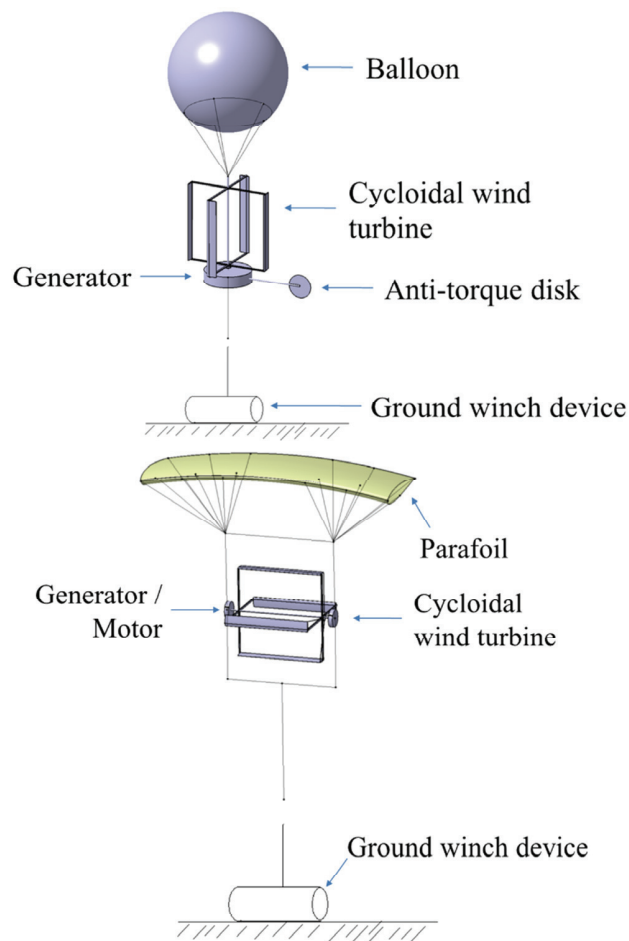


Fig. 1. High altitude cycloidal wind turbines

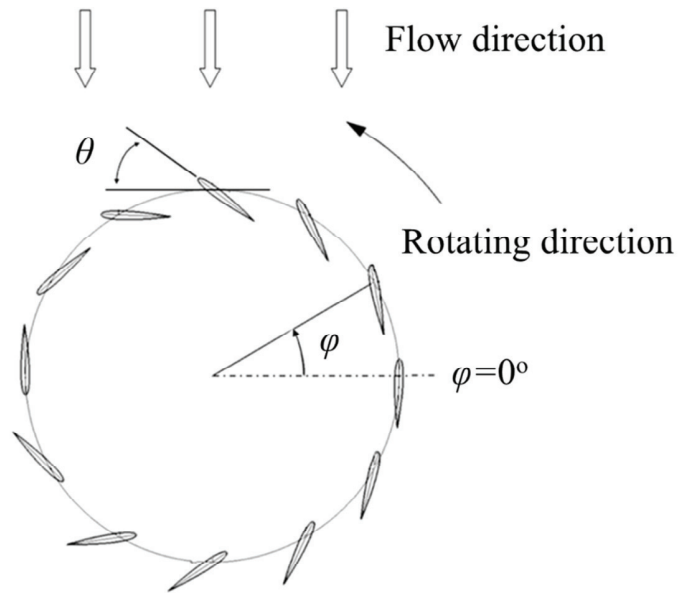


Fig. 2. Schematic view of cycloidal rotor blades



Fig. 3. Applications of cycloidal rotor

For sample calculation, the rotor size was determined as 10 meters diameter and 10 meters blade span length. Rotor components structural sizing was carried out with the assumption that almost all structures are made of aluminum alloy. Rotating blades simply supported at both ends should withstand centrifugal force. The maximum rotor rotating speed was determined by tip speed ratio and cut-out wind speed. In this rotor design, tip speed ratio was assumed as 2.2 and cut-out wind speed of 20m/s was applied. NACA0018 airfoil section shaped blade was designed according to the rotor blade displacement calculation by simple static equation. Table 1 shows rotor components weight summary. The total rotor weight was estimated as 564kg including four blades and other structural parts. The generator weight was assumed as 200kg.

Table 1. Cycloidal rotor components weight

Part	Unit weight (kg)	# of unit	Weight (kg)
Blade	70	4	280
Hub arm	16	8	128
Hub	8	2	16
Axis	60	1	60
Control device	50	1	50
Misc.	30	-	30
Total			564

A long-term study wind data in open sea area in Hong Kong were applied to calculate the whole system performance [11]. The average values of thirty years (1968-1997) and two parameters for Weibull distribution were adopted and analyzed. Wind speed profile with height was estimated under neutral stability conditions by Deacon's equation. Air and helium density variation as a function of altitude was also estimated by US standard atmosphere model. Based on this environmental condition, two different wind turbine models were designed up to 1,500 meters height. Figure 4 shows three different wind speed distributions with shape parameter 2.03 and scale parameter 8.29.

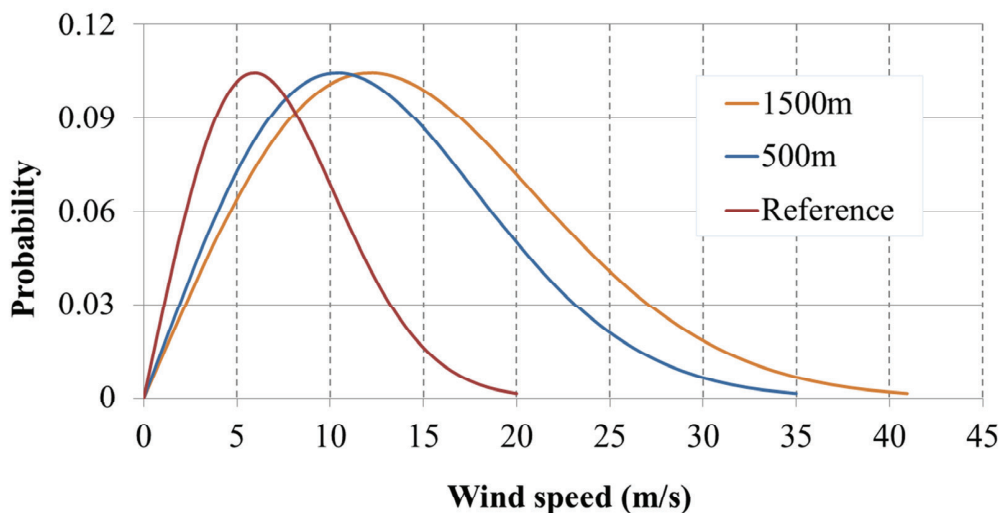


Fig. 4. Weibull distributions of three different height

3. Balloon Tethered Wind Turbine

A tethered balloon is applied to lift the cycloidal wind turbine system as shown in Fig. 1. The balloon is filled with buoyant helium gas and it is assumed as spherical shape. The cycloidal wind turbine with electric power generator is located below the balloon. The rotating axis is parallel to the tethering cable. A set of winch devices on the ground holds the airborne system using the tether line.

The average wind speed is 7.3m/s at the reference height under the given Weibull distribution condition. It becomes 12.8m/s at 500m height and 15.0m/s at 1,500m height. The generated power, 15.5kW at the reference

height, is increased as 58.9kW and 71.6kW, respectively. In this calculation, rotor efficiency was assumed as 35%. Rotor operating cut-in speed of 3m/s was applied and it was assumed that wind turbine rated power is reached at wind speed of 20m/s. Table 2 shows some designed values of balloon system at 1,500 meters condition. In this design, 10% additional lift to the total weight was considered. The volume of ballonnet was 10% of the entire balloon envelope. Some details were referenced from the previous research [7, 12].

Table 2. Balloon characteristics

Parameter	Value	Remark
Balloon diameter	15.1 m	
Balloon volume	1803 m ³	
Static lift	1466 kg	
Balloon fabric weight	179 kg	0.25 kg/m ²
Balloon pressure controller weight	30 kg	
Rigging ropes and patches weight	20 kg	
Tether cable weight	350 kg	0.2 kg/m (including load terminating weight 50kg)
Total system weight	1343 kg	

4. Parafoil Tethered Wind Turbine

As another high altitude wind turbine, a tethered parafoil is applied to cycloidal rotor as shown in Fig. 1. The cycloidal rotor is mounted at the parafoil with a way that its axis is parallel to the ground, which means 90 degrees different from the balloon tethered model. The rotor generates lifting force at low altitude to make the whole system go up to the target altitude. Then, the rotor changes its mode to produce electricity. If the wind speed becomes insufficient to maintain the altitude by parafoil alone, the rotor produces supplementary lifting force through mode conversion. The parafoil described in this paper is that of the NASA X-38 vehicle test [5]. Some basic data of parafoil such as area and weight were adopted as it is except aerodynamic lift coefficient. Table 3 shows geometric values of parafoil. Aerodynamic lift coefficient was estimated by CFD analysis as 1.05 [13].

Two kind of wind speed was defined in this parafoil tethered wind turbine system. One was mode conversion related wind speed and the other was the whole system cut-in wind speed. These values at 1,500m height are 6.4m/s and 3.5m/s, respectively. The cycloidal rotor produces lifting force to maintain the altitude between these two wind speed ranges. The maximum required lifting force at mode conversion wind speed is 1,114kg which is difference between the whole wind turbine system weight and the parafoil weight. In this condition, the cycloidal rotor rotating speed becomes 56rpm with 25 degrees blade pitch angle. Its energy consumption is about 200kW for the most critical condition. Figure 5 shows energy variation for the whole operating wind speed range. Energy consumption decreases almost linearly as wind speed becomes higher. The rotor energy generation increases by cubic order until it reaches rated power wind speed. By multiplying the Weibull distribution wind speed probability in Fig. 4 and the energy variation in Fig. 5, the rotor power generation values are calculated. Total required energy for lifting force generation becomes 7.2kW, while the parafoil tethered wind turbine generates 71.2kW over the mode conversion wind speed range. Therefore, the calculated total power generation at 1,500m height is approximately 64.0kW based on these parameters. Comparing with the balloon tethered model, the power output is about 10% smaller; however, the parafoil produces much more lifting force at high speed wind condition. This means that the cycloidal rotor could be larger. If the rotor size becomes 15m by 15m, it produces 2.25 times more energy.

Table 3. Parafoil data

Parameter	Value
Area	696.8 m ²
Span length	43.6 m
Weight	483.7 kg

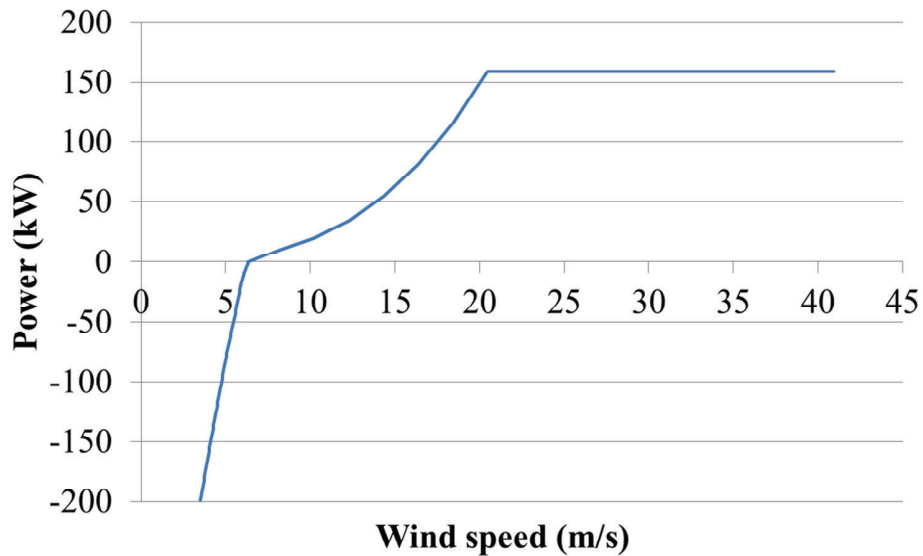


Fig. 5. Power generation and consumption variation of parafoil tethered wind turbine

5. Conclusion

Two models in this paper have their own characteristics. Balloon tethered wind turbine is more stable and easier to control; while, parafoil tethered rotor could be designed to produce much more energy at high wind speed condition. The conceptual design shows that it can be a feasible plan for an alternative wind turbine as a small and independent energy generation device as well as large and grid application. In addition to this study, overall system dynamics and electric system design are necessary for more reliable results.

References

- [1] Wikipedia, Wind power, http://en.wikipedia.org/wiki/Wind_power (Accessed April 16 2013).
- [2] Wikipedia, Wind turbine design, http://en.wikipedia.org/wiki/Wind_turbine_design (Accessed April 16 2013).
- [3] Fagiano L, 2009, Control of Tethered Airfoils for High-Altitude Wind Energy Generation, PhD Thesis, Politecnico Di Torino.
- [4] Shelke KN and Duraphe MD, 2012, Magenn Air Rotor System, International Journal of Engineering Research and Applications, Vol. 2, Issue 6, pp.1566-1568.
- [5] Kim J and Park C, 2010, Wind power generation with a parawing on ships, a proposal, Energy, Vol. 35, pp.1425-1432.
- [6] Bronstein MG, 2011, Harnessing rivers of wind: a technology and policy assessment of high altitude wind power in the U.S., Technological Forecasting and Social Change, Vol. 78, pp.736-746.
- [7] Hwang IS, Kang W and Kim SJ, 2011, An Airborne Cycloidal Wind Turbine Mounted Using a Tethered Balloon, International Journal of Aeronautical and Space Sciences, Vol. 12, No. 4, pp.354-359.

- [8] Hwang IS, 2009, Numerical and Experimental Study on Design and Development of Quadrotor Cyclocopter, PhD Thesis, Seoul National University.
- [9] Hur CM, Min SY, Lee CH, Seung MH and Kim SJ, 2013, Numerical Study on Cycloidal Rotor Rotating Direction for Cyclocopter Forward Flight, The Korean Society for Aeronautical & Space Sciences Spring Conference.
- [10] Hwang IS, Lee YH and Kim SJ, 2009, Optimization of cycloidal water turbine and the performance improvement by individual blade control, *Applied Energy*, Vol. 86, pp.1532-1540.
- [11] Lun IYF and LAM JC, 2000, A study of Weibull parameters using long-term wind observations, *Renewable Energy*, Vol. 20, pp.145-153.
- [12] Kang W, 2008, Gust Response Analysis of 32m Aerostat, PhD Thesis, Korea Advanced Institute of Science and Technology.
- [13] Hwang IS, Kang W and Park YM, 2012, High Altitude Cycloidal Wind Turbine System Design using Parafoil, The Korean Society for Aeronautical & Space Sciences Spring Conference.